AFRL-SR-AR-TR-05-

0730

REPORT DOCUMENTATION PAGE

OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
23-03-2005	Final Technical Report	January 1, 2004 - December 31, 2004

4. TITLE AND SUBTITLE
Developing a Research Road map on Performance Limiting Flow Processes in High-Stage Loading Compressors

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-04-1-0060

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Tan, Choon S., Ph.D.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technology
Gas Turbine Laboratory, 31-267
77 Massachusetts Avenue
Cambridge, Massachusetts 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. John Schmisseur
Air Force Office of Scientific Research
875 North Randolph Street, Room 3112
Arlington, Virginia 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This document constitutes the final report on a research program on "Developing a Research Roadmap on Performance Limiting Flow Processes in High-Stage Loading Compressors." The focus is on developing the required research framework and tasks to address the fluid dynamic difficulties of highly loaded, high Mach number (HLHM) compressor stages. These consist of identifying the database available on such compressor stages, developing a plan to determine what additional data are needed, and defining the steps needed for successful execution of the research program in collaboration with the AFRL (Air Force Research Lab), NASA GRC and Rolls-Royce Inc. Indianapolis. The framework under which these tasks have been developed is based on hypothesis that the fluid dynamic difficulties encountered are linked to two specific flow processes in high-stage loading, high Mach number compressor stages.

15. SUBJECT TERMS
aerothermodynamics of high-mach number high loading compressor

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU	18	Choon S. Tan
					19b. TELEPHONE NUMBER *(Include area code)* 617-253-7524

Gas Turbine Laboratory
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139

Final Report on AFOSR Grant FA9550-04-1-0060

entitled

DEVELOPING A RESEARCH ROADMAP ON PERFORMANCE LIMITING FLOW PROCESSES IN HIGH-STAGE LOADING COMPRESSORS

submitted to

Air Force Office of Scientific Research
875 North Randolph Street
Room 3112
Arlington, VA 22203

ATTN: Dr. John Schmisseur

PRINCIPAL INVESTIGATOR: Dr. Choon S. Tan
Senior Research Engineer, Gas Turbine Laboratory

PERIOD OF INVESTIGATION: January 2004 – December 2004

March 2005

TABLE OF CONTENT

1.0 ABSTRACT

This document constitutes the final report on a research program on "Developing a Research Roadmap on Performance Limiting Flow Processes in High-Stage Loading Compressors". The focus is on developing the required research framework and tasks to address the fluid dynamic difficulties of highly loaded, high Mach number (HLHM) compressor stages. These consist of identifying the database available on such compressor stages, developing a plan to determine what additional data are needed, and defining the steps needed for successful execution of the research program in collaboration with the AFRL(Air Force Research Laboratory), NASA GRC and Rolls-Royce Inc Indianapolis. The framework under which these tasks have been developed is based on the hypothesis that the fluid dynamic difficulties encountered are linked to two specific flow processes in high-stage loading, high Mach number compressor stages. One is the interaction between shear layers from one blade row and the shock systems from a downstream blade row. The second is the enhanced influence of unsteadiness, from adjacent blade rows on leakage flow at rotor or stator end gaps, in high Mach flow regimes.

2.0 INTRODUCTION AND BACKGROUND

A strong incentive exists to reduce airfoil count in aircraft engine core compressors. A driver for this is the desire for affordability (the first A in the Air Force acronym VAATE – Versatile, Affordable, and Advanced Turbine Engine). A basic constraint on blade reduction is seen from the Euler turbine equation, which shows that, although a design can be carried out in different ways to obtain increased stagnation enthalpy rise, and hence pressure ratio, with fewer blades or fewer blade rows, one must increase blade loading and/or wheel speed. For the largest impact both loading and wheel speed must increase, with the consequence that the regime of operation consists of highly loaded blades at transonic Mach numbers. One can perhaps articulate the likely technical challenges encountered in this class of compressors by reference to Figure 1; this Figure categorizes compressor design in terms of Mach number versus design point stage loading. Four categories of compressor stages are shown, from low-loading, low-speed

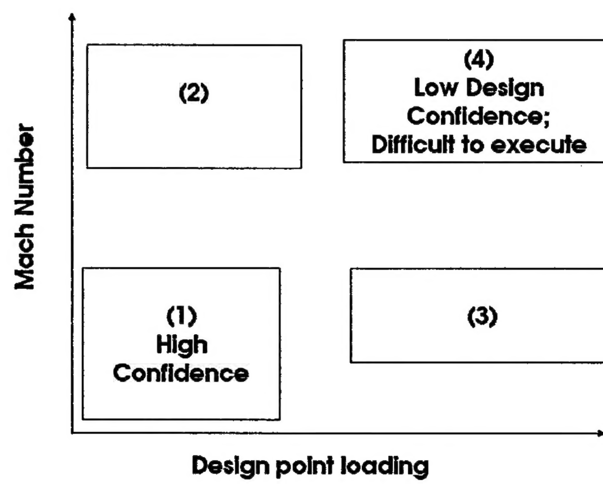

Figure 1: Notional classes of compressor design in Mach number vs design point loading space.

(type 1) to HLHM (type 4). Categories 2 and 3 are notional, and we thus contrast types 1 and 4 in terms of blade row coupling and effects on performance. For compressors in flow regimes represented by type 1 (and presumably to a large extent for types 2 and 3) the effects that have to do with multiple blade rows have been addressed and quantified. For example, Smith (1993) states that "multistage turbomachines have increased

performance when the axial gaps between blade rows are reduced", presents a mechanism for a major part of this increase (reversible work transfer to a wake as it passes through a succeeding blade row and consequent decrease in mixing losses) and quantifies the effect with a simple model. Computations on this point (Valkov and Tan, 1999) show agreement with this idea. The effect of tip leakage flow on succeeding stages has also been quantified for this regime (Valkov and Tan, 1999; Sirakov and Tan, 2003). For such stages, therefore, the effects have not only been addressed to a large extent, but their effect on machine performance has been estimated.

The observation, however, is that this situation is not true for compressors in flow regimes of type 4. The difficulties that the technical community has experienced in implementing designs in this regime are one indication. A further indication may be seen in the data in Figure 2 (Hetherington and Moritz, 1977), which shows performance from a multistage compressor at two speeds. The data are for two different blade spacing. At the lower speed there is a slight increase in efficiency and pressure rise at the smaller blade spacing in agreement with the computational simulations referred to above and with other low speed experimental results (Smith, 1970; Mikolajczack, 1977). At the higher speed shown, however, there is a decrease in performance with the smaller spacing, i.e., a *qualitatively* different behavior. Further the magnitude of the change is much larger than at the lower speed.

The observed qualitative change suggests that there could be new effects that occur at high speed. For example a plausible new effect could be the unsteady interaction of shock systems with shear layers (e.g. shocks propagating upstream from a rotor which affect the behavior of shear layers both within and downstream of the stator row). This mechanism has been shown to result in the thickening of the shear layers, increase in flow blockage (analogous to boundary layer displacement thickness), and consequent additional entropy generation thus lowering the efficiency (Gorrell and Okiishi, 2003; Gorrell *et al.*, 2003).

Another, and different, plausible cause could be the interaction of several phenomena, which are understood in isolation but whose combined effect can give rise to

qualitatively different behavior at high Mach numbers and loading. One may thus argue that, the understanding, empiricism, and guidelines which apply well to machines of lower Mach number and loading may not apply to HLHM compressors.

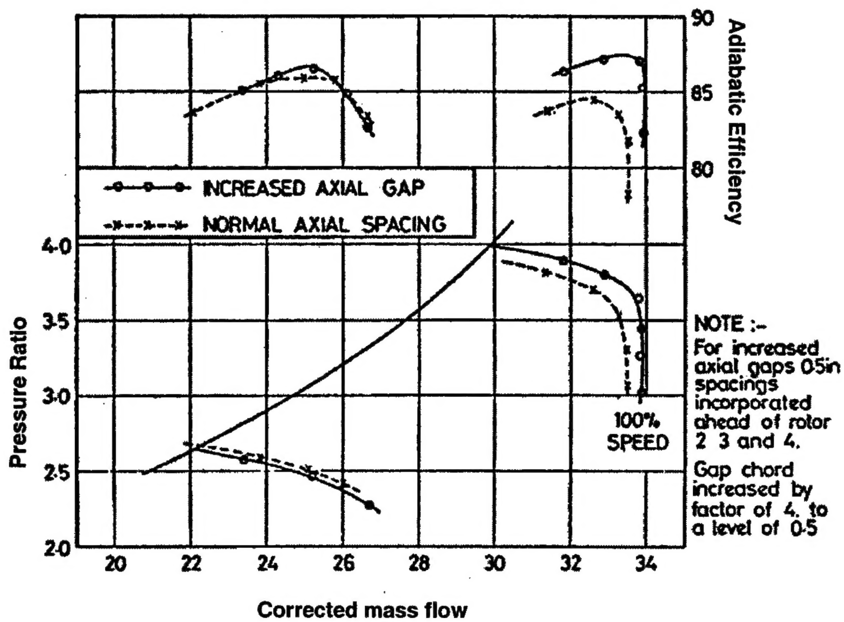

Figure 2: The effect of axial spacing on the performance of a 4-stage high pressure compressor (Hetherington and Moritz, 1977).

The above flow interaction effects are hypothesized to be plausible causes for the substantial difficulties encountered in obtaining efficient performance at design as well as in *retaining* this efficiency in response to geometric and operational variability in HLHM compressors. As such an overall goal is thus developing a research roadmap for addressing the fluid dynamic difficulties of these highly loaded, high Mach number[1] (HLHM) compressor stages. This involves the implementation of the following tasks: (i) identifying the database available on compressor stages that are representative of high-stage loading and high Mach number design, (ii) proposing a plan to determine what

[1] By high Mach number stage we mean core compressor stages that operate at conditions with the flow supersonic over most of the span in a flow regime in which the properties of the passage flow are sensitive to small changes in inlet or exit conditions.

additional data must be developed for addressing the associated fluid dynamic difficulties, and (iii) defining the steps needed for successful execution of the research program in collaboration with the AFRL(Air Force Research Laboratory), NASA and Industry turbomachinery research communities. The framework under which these tasks will be carried out is based on the hypothesis that the fluid dynamic difficulties encountered are linked to two specific flow processes in high-stage loading, high Mach number (HLHM) compressor stages. One is the interaction between shear layers from one blade row and the shock systems from a downstream blade row. The second is the enhanced influence of unsteadiness, from adjacent blade rows on leakage flow at rotor or stator end gaps, in these flow regimes. The implementation of Task (i) to (iii) is described.

This report is organized as follows. First the research questions are stated followed by a brief description of the data identified to-date as well as data to be further made available and acquired. Procedure for extracting relevant flow information and figures of merit/parameters from data to establish causal link between unsteady flow phenomena and compressor performance is presented. Proposed future research is also delineated.

3.0 RESEARCH QUESTIONS AND ISSUES

The research questions to be addressed for assessing the above hypothesis are:

1. What flow changes are due to unsteady interactions between shock waves and shear layers (viscous layer on solid surfaces, wakes, and leakage vortex at rotor or stator end gaps) and leakage flow response to unsteady forcing from adjacent blade rows?
2. How are these changes connected to: (i) peak efficiency and (ii) peak pressure rise of HLHM compressors (i.e. what is the impact of high loading and high Mach number on efficiency potential and why, in the sense of what mechanism is responsible, does this occur)?
3. What are the basic fluid dynamic scalings that characterize the effects of coupling between blade rows?

4. What physical mechanisms govern the sensitivity of the efficiency and pressure ratio to clearance (both rotor tip and stator end gap) in these machines?
5. What levels of model are needed to appropriately capture these effects on the performance HLHM compressors?

4.0 AVAILABLE DATABASE ON HIGH LOADING HIGH MACH NUMBER COMPRESSORS

In identifying database available on compressor stages, it is important to have access to geometries and experiments in parameter space representative of HLHM compressors. To address this point, use can be made of information from several HLHM compressor stages. One is the AFRL transonic SMI (Stage Matching Investigation) compressor stage, consisting of an inlet guide vane (IGV) followed by a rotor-stator stage, with variable axial spacing between IGV and rotor. There are also three NASA-RRI (Rolls Royce Indianapolis) two-and-half stage HLHM-compressors (two without and the other with forward sweep blade configuration). The design characteristics of these machines are summarized in Table 1.

The latter three compressors have been designed and developed as highly loaded multistage Advanced Small Turboshaft Compressor (ASTC). This type of compressors is representative of those use in small machines and rear stages of larger compressors in large machines. The SMI fan/compressor stage discussed in Section 4.1 below would be more representative of the front stages of larger compressors. Thus the use of these two types of compressor stage as research articles to base the research program on should enable the generalization of results to a broad class of HLHM compressor stages.

An outline of the data currently available from these compressors is given below.

4.1 AFRL SMI One-and-half Stage Compressor

The AFRL SMI 1.5-stage compressor, shown in Figure 1, can be of the following configurations:

(1) Unloaded IGV followed by a rotor-stator stage:

The unloaded IGV (inlet guide vane) serves as a wake generator (Gorrell *et al.*, 2003a; Gorrell *et al.*, 2003b). The following measurements are available for IGV-rotor axial spacings of 0.13, 0.26, and 0.55 of IGV mean chord:

(i) PIV (particle image velocimetry) for operating points from choke to stall at 100% corrected speed;

(ii) High response pressures over the rotor from choke to stall at 100% corrected speed;

(iii) High response pressures at 50% and 75% span on IGV at 70% chord from choke to stall at 100% corrected speed;

(iv) total pressure and temperature rakes downstream of stator from choke to stall at 100% corrected speed.

Computations available for two IGV-rotor axial spacings 0.13 and 0.55 of IGV chord are:

(i) APNASA[2] (Adamczyk et al., 1990) simulations for 1.5 stages at 100% corrected speed;

(ii) MSU Turbo (Chen and Briley, 2001) unsteady three-dimensional solutions at 100% corrected speed for peak efficiency and near stall. These unsteady calculations have been carried out for an IGV-rotor pair with an imposed downstream pressure boundary condition that reflects the presence of the downstream stator.

(2) Loaded IGV followed by a rotor-stator stage:

The loaded IGV is designed to be a more representative simulation of a stator. Measurements (similar to those for configuration (1) above) for three IGV-rotor spacings will be completed by November 2004. Computations for at least two IGV-rotor spacings , 0.13 and 0.55 of IGV chord, will be completed by November 2004 (unsteady 3D computations for a loaded IGV-rotor pair using MSU Turbo at 100% corrected speed for peak efficiency and other operating points in proximity of the peak efficiency).

[2] APNASA is flow solver for calculating flow in multistage compressor configuration developed at NASA GRC.

Table 1: Design parameters for the three research compressors: in column 3, the first number pertains to the first stage, the second to the second stage. (Courtesy of CARL AFRL, NASA GRC and Rolls-Royce Indianapolis)

Design parameters	**AFRL SMI 1.5-Stage**	**NASA-RRI unswept/swept 2.5-Stage**
Pressure Ratio	~1.9	~5.1
Aspect Ratio, Rotor	0.916	0.73/0.80
Aspect Ratio, Stator	0.824	0.68/0.55
Solidity (mid), Rotor	1.89	2.0/1.7
Solidity (mid), Stator	1.65	1.75/1.83
D-Factor (tip), Rotor	0.541	0.616/0.502
D-Factor (hub), Stator	0.506	0.513/0.350
Rotor relative Mach number (tip)	1.4	1.68/1.38
Mach number(hub), Stator	0.83	
Rotor Inlet Swirl (mid)	0	0.0/5.7

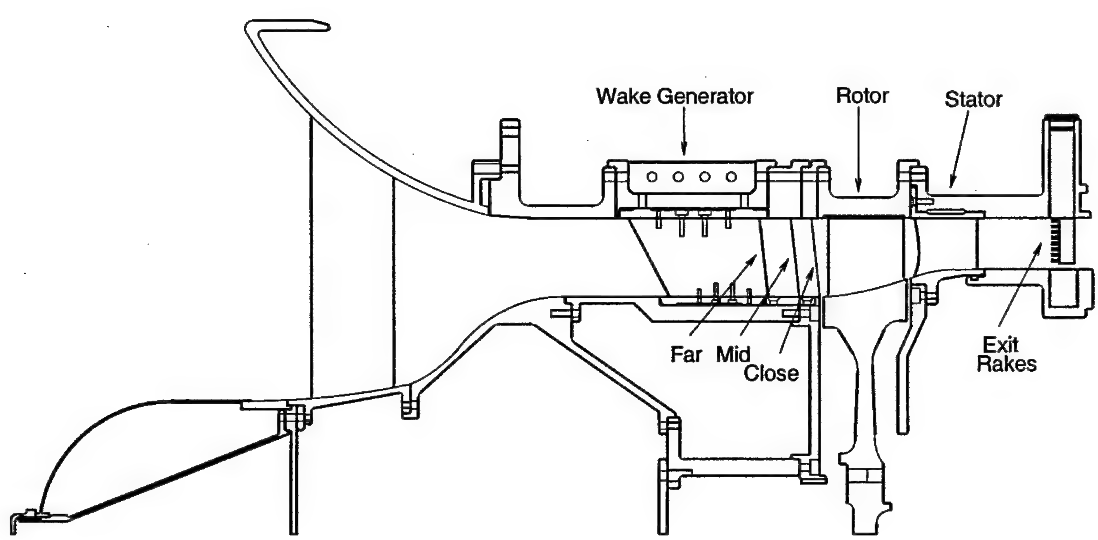

Figure 1: Stage matching investigation rig layout (Gorrell et al., 2002; courtesy of CARL at AFRL).

(3) Unloaded IGV, rotor-stator stage with a brush shroud (i.e. with a rotor tip seal):

This configuration has an effective tip clearance different from configuration (1) above. Measurements (similar to those for configuration (1)) for three IGV-rotor spacings will be completed in December 2004. Computations will be added as needed to answer the research questions.

(4) Loaded IGV followed by a rotor-stator stage with a brush shroud (rotor tip seal):

This configuration has an effective tip clearance different from configuration (2) above. Computations and experiments will be planned as needed (through discussions with the collaborative teams) to address the research questions.

The experiments for SMI configurations have been, and will be, conducted at the Compressor Aerodynamic Research Laboratory (CARL) at AFRL.

4.2 NASA-RRI HLHM Compressor Configurations

There are three compressor configurations available: an Original Baseline configuration with two and half stages, a New Build Baseline configuration with two and half stages, a Forward Swept configuration with two stages consisting of a forward swept rotor. All the three configurations have nearly the same high pressure ratio. Test data are available for Original Baseline two and half stage configuration, Forward Swept one stage as well as two-stage configuration, Baseline New Build one-stage configuration as well as two-stage configuration.

The data to support the research (measured as well as computed) available for these compressors includes:

(1) Test measurement data:

Overall performance speedline characteristics (multiple speeds from 70%-102.5%);

Stage 1 performance speedline characteristics (multiple speeds from 70%-102.5%);

Spanwsie distributions of stagnation pressure and stagnation temperature at inlet, stator inlet, and discharge (multiple speeds from 70%-102.5%);

Unsteady static pressure distributions above build 1 rotor 1 at different throttle positions (100 and 102.5% speed).

(2) Computed flow fields from Steady and unsteady CFD simulations

The computed flow fields for these three compressors based on APNASA, ADPAC , and OCOM3D CFD code (Hansen and Delaney, 1996) will also be made available by Rolls-Royce Indianapolis and NASA GRC for a proposed research program on "Performance Limiting Flow Processes in High-Stage Loading High Mach Number Compressors".

The utility of this data on these compressor designs will be to provide another diagnostic for the findings of the research on the SMI 1.5 stage, including aspects such as the observed choke margin sensitivity, sensitivity to stator end gap leakage flow, and sensitivity to change in corrected speed. Additional work for these HLHM designs will include determining sensitivity of performance to geometry variations as well as additional unsteady numerical simulations to address the research questions. The additional numerical simulations needed for answering the research questions are to be implemented using MSU Turbo (Chen and Briley, 2001). NASA GRC has granted MIT the license to use MSU Turbo in turbomachinery research. MSU Turbo is currently in place on the MIT Gas Turbine Laboratory for calculating unsteady 3D flow in compressor stages.

5.0 FRAMEWORK OF APPROACH FOR CONNECTING UNSTEADY FLOW PHENOMENA TO TIME-AVERAGE PERFORMANCE (EFFICIENCY AND PRESSURE RATIO)

This section describe the framework for processing, organizing, interrogating and making physical understanding of the (computational as well as experimental) data delineated in Section 4.0 above.

Specific steps for extracting relevant flow information and figures of merit/parameters from data (computed as well as measured) to connect unsteady flow phenomena with achievable efficiency and pressure rise consist of the following three different levels:

i) Detailed unsteady flow processes within the blade rows,

ii) Consistent assessment of the time-mean footprint of these processes, and

iii) Impact on overall stage characteristics (efficiency and peak pressure rise capability).

These have been dictated by the fact that there are many different length and time scales in turbomachines, with a corresponding spectrum of unsteady processes; determining which of these are important, and defining explicit causal links between flow details and overall metrics is thus a key part of the research road map.

We can describe the conceptual framework for bringing together these different levels of information. The unsteady three-dimensional flow at the rotor-stator blade passage level includes details of flow processes such as unsteady interactions of shear layers (wakes, leakage vortex, and viscous layers) with shocks, and unsteady fluctuation in the leakage flow in response to flow unsteadiness from adjacent blade rows. Of interest here are local regions of entropy production, as well as regions in which the flow changes are such as to cause additional entropy increase downstream. At this first level the fluid mechanic processes are most visible but their effect is not.

The second level is thus assessing the time-mean footprint of the unsteady processes. While the time-average flow can be computed from the unsteady three-dimensional flow via time-averaging over several cycles of blade-passing time periods, to determine the time-average impact of the unsteady interactions we need to define an

analogous steady flow to which the time-average flow can be compared[3]. One can think of this comparison, posed in a consistent manner, as asking the question "How would the flow be different if the unsteadiness were absent?"

The third level of information is essentially the overall blade row performance quantities such as efficiency and flow blockage (a measure of the degradation in the pressure rise capability of the blade passage). Efficiency can be directly linked to the entropy production (or the potential entropy production, for example in non-uniformities that are not yet mixed out). Procedures for extracting normalized flow blockage across a blade passage have been developed and used in the work reported by Khalid *et al.* (1999) on tip clearance flow, Shum *et al.* (2000) on centrifugal impeller-diffuser interaction, Sirakov and Tan (2003) on unsteady wake and tip clearance blade effects on stator performance, and by Shabbir and Adamczyk (2004) for casing treatment operation. From this perspective, although the proposed research clearly reaches beyond the cited work, the point is that procedures (and the ideas that underpin them) exist that can be used to attack the problems described; comparison of the normalized blockage and entropy increase extracted from the time-average flow to that from the equivalent steady flow enables direct identification of the impact of specific flow processes. In sum, the progression through these different levels provides a means of (and a traceability for) identifying the flow features that set the achievable stage efficiency and pressure ratio.

For instance, computations presently available and proposed for the SMI 1.5 stage for unloaded IGV and loaded IGV, for various IGV-rotor spacings, rotor-stator spacings, and for various rotor tip clearances enable assessment of the sensitivity [*d*(output)/*d*(input)] of efficiency, blockage, and pressure ratio to features such as

---

[3] There is no unique way of defining an "equivalent" average steady flow from an unsteady flow field (or an equivalent one-dimensional average from a spatially non-uniform flow). There are five conservation principles (mass, three momentum, and energy) so that the averaging process necessarily means that some variables will not be captured. For example, if each variable of interest is time-averaged separately, the resulting averaged steady flow field is inconsistent; the average stagnation pressure from the unsteady solution is different than the stagnation pressure calculated from the averaged Mach number and static pressure. There are, however, approaches which retain the features that are most relevant (Greitzer *et al.*, 2004].

loading, intra-blade gap, and tip clearance changes. Framing the analysis, and the synthesis of the computed flow field at the three levels described, should allow causal links between flow features and sensitivity in efficiency, pressure ratio, and blockage. The measurements presently available and to be acquired on the SMI 1.5 stage as indicated above, though not as finely distributed as one could obtain from numerical experiments, should serve to corroborate the computations on different levels (e.g. PIV measurements and high response pressures identifying unsteady flow features and associated time scales and can be coupled with performance measurements).

6.0 OVERALL SUMMARY

Available database, both from experimental/test rigs as well as computations, on representative HLHM compressor stages from AFRL CARL and RRI/NASA have been identified. The data is deemed to be useful for addressing fluid dynamic difficulties encountered in HLHM compressor stages. A plan has also been developed to determining what additional data is needed; the data includes both experimental as well as computational. The proposed tool for calculating unsteady three-dimensional flow in HLHM compressor stages is MSU Turbo which has been put in place for research use at the MIT Gas Turbine Laboratory. A conceptual framework of approach for connecting unsteady flow phenomena to time-average performance (efficiency and pressure ratio) of HLHM compressors has been developed. The framework under which research will be implemented is based on the hypothesis that the fluid dynamic difficulties encountered are linked to two specific flow processes in high-stage loading, high Mach number (HLHM) compressor stages. One is the interaction between shear layers from one blade row and the shock systems from a downstream blade row. The second is the enhanced influence of unsteadiness, from adjacent blade rows on leakage flow at rotor or stator end gaps, in these flow regimes.

7.0 REFERENCES

Chen, J.P., Briley, W. R., 2001, "A Parallel Flow Solver for Unsteady Multiple Blade Row Turbomachinery Simulations," ASME-2001-GT-0348.

Gorrell, S., Okiishi, T., Copenhaver, W., 2003, "Stator-Rotor Interactions In A Transonic Compressor: Part 2 – Description of a Loss Mechanism", ASME *Journal of Turbomachinery*, Vol.125.

Gorrell, S., Okiishi, T., Copenhaver, W., 2003, "Stator-Rotor Interactions In A Transonic Compressor: Part 1 - Effect Of Blade-Row Spacing On Performance", ASME *Journal of Turbomachinery*, Vol. 125.

Greitzer, E.M., Tan, C.S., Graf, M.B., 2004, *Internal Flow: Concepts and Applications*, Cambridge University Press.

Hansen, J. L., Delaney, R. A., 1996, "Task 4: Advanced Small Turboshaft Compressor (ASTC) Performance and Range Investigation", NASA Contractor Report 198503

Hetherington, R., Moritz, R. R., 1977, "The Influence of Unsteady Flow Phenomena on the Design and Operation of Aero Engines", *Unsteady Phenomena in Turbomachinery*, AGARD CP-177, North Atlantic Treaty Organization.

Mikolajczack, A. A., 1977, "The Practical Importance of Unsteady Flow", *Unsteady Phenomena in Turbomachinery*, AGARD CP-144, North Atlantic Treaty Organization.

Shabbir, A., Adamczyk, J.J., 2004, "Flow Mechanism for Stall Margin Improvement Due To Circumferential Casing Grooves On Axial Compressors," ASME-GT2004-53903.

Shum, Y.K., Tan, C. S., Cumpsty, N. A., 2000, "Impeller-Diffuser Interaction in Centrifugal Compressor," *ASME J. Turbomachinery*, Vol. 122, No. 4.

Smith L.H., 1970, "Casing Boundary Layers in Multistage Axial Flow Compressors", *Flow Research on Blading*, L.S. Dzung, ed., Elsevier Publishing Company.

Smith, L.H., 1993, "Wake Ingestion Propulsion Benefits", *J. Propulsion & Power*, Vol. 9, No. 1.

Sirakov, B., Tan, C. S., 2003, "Effect Of Unsteady Stator Wake – Rotor Double-Leakage Tip Clearance Flow Interaction On Time-Average Compressor Performance", ASME *J. of Turbomachinery*, Vol. 125, No. 3.

Valkov, T., Tan, C.S., 1999, "Effects of Upstream Rotor Vortical Disturbances on Time-Average Performance of Axial Compressor Stator: Part 1- Framework of Technical Approach and Rotor Wakes-Stator Blade Interaction, and Part 2- Rotor Tip Leakage and Discrete Streamwise Vortex -Stator Blade Interaction" *ASME J. Turbomachinery,* Vol. 121, No. 3.

8.0 PERSONNEL WORKING ON THIS RESEARCH PROJECT

MIT Faculty and Staff:

C. S. Tan	Senior Research Engineer
E. M. Greitzer	Slater Professor of Aeronautics and Astronautics

MIT Graduate Students:
None

AFRL Points of Contact:
Dr. Steve Puterbaugh, (937) 255-7432 (email: steven.puterbaugh@wpafb.af.mil),
Dr. S. Gorrell, (937) 255-7344 (email: steven.gorrell@wpafb.af.mil)
Mr. D. Car, (937) 255-7326 (email: david.car@wpafb.af.mil)

Technical Meetings at MIT in November 2003 and at NASA GRC on March 10, 2004.

NASA Glenn Points of Contact:
Dr. A. Strazisar, (216) 433-5881 (email: Anthony.J.Strazisar@grc.nasa.gov)
Dr. J. Adamczyk, (216) 433-5829 (email: John.J.Adamczyk@lerc.nasa.gov)

Rolls Royce Indianapolis Points of Contact:
Dr. S. Wellborn, (317) 230-4706 (email: Steven.R.Wellborn@Rolls-Royce.com)

9.0 PUBLICATIONS

None

10.0 PATENTS AND INVENTIONS

None